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# "Describing the elephant": A framework for supporting sustainable development processes

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ABSTRACT

Sustainable development and participatory governance are among the central policy priorities of our time. The challenge is at all scales of development and participation. Finding and validating methodological approaches has become urgent.

Existing decision processes such as multi-criterion decision analysis (MCDA), multi-objective decision making (MODM), life cycle assessment (LCA) and cost-benefit analysis (CBA) are frequently used, with varying degrees of satisfaction reported. It appears that sustainable development can be assessed and analysed in different ways, any of which may be of use but none of which seems to be complete. The use of all, however, appears to involve such complexity as to be not feasible.

There is a need for a more integrated and systematic approach to decision-making. In this paper, existing decision aid processes and frameworks are reviewed, and a novel evolutionary approach is proposed that can support them all.



**Contents**



John Godfrey Saxe's [1] poem of "The Blind Man and the Elephant" tells of several blind men asked to describe an elephant. The man who reaches the elephant's side says that the unknown animal resembles a wall; the man bumping into the tusk concludes that the unseen creature resembles a spear; while the third, feeling the trunk, declares it to be like a snake. In the end, those of us who can see the elephant know that each individual is both right and wrong: what is missing is the vision needed to put all of the pieces into a comprehensive whole. You are urged to read all the papers in this series that are the result of research on sustainable development frameworks. They are listed at the end of this paper.

## 1. Introduction

Sustainable development and participatory governance are among the central policy priorities of our time. The challenge is

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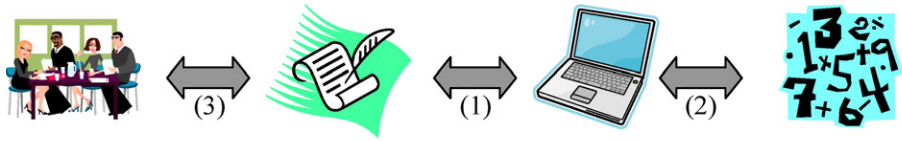


**Fig. 1.** Process overview.

at all scales of development and participation. There are numerous examples, such as of climate change mitigation and adaptation, water provision and sanitation, food supply, economic aid and so on. The challenge requires an understanding and application of a clear, coherent and comprehensive approach. Finding and validating methodological approaches has become urgent.

The word "sustainable" means "able to be sustained" while "to sustain" means variously "to hold up" or "to keep going". It derives from the Latin root sustinere, meaning to hold up or sustain. There is a considerable etymology of the word dating back to the 13th century. The word "development" means "economic advancement" or "the action of developing land". The word "participatory" means "of taking part" and the word "governance" means "act or manner of governing".

The words "sustainable", "development", "participatory" and "governance" refer to "program(me)s", or "definite plans of intended proceedings". If a program is part of another program, then it "sustains", and "is sustained by", the other: the proceedings of the programs are mutually dependent. For example, one company's definite plan to cut greenhouse gas (GHG) emissions, if part of one overall Earth definite plan for cutting GHG emissions, forms one integrated "sustainable program" for cutting GHG on Earth. Likewise, if a program is part of another it "develops", "participates in" and "governs" the other, and vice versa.

Because we are mortal, the proceedings of programs will outlive us. They therefore refer to happenings in the environment and are all, ultimately, decisions concerning "mass-equivalents" (mass or energy). Decisions can involve: (1) quantities of the same quality of mass-equivalent; (2) quantities of different qualities of mass-equivalents; and (3) participants.[1] The diversity of participants and qualities of mass-equivalents to decisions have increased greatly recently. This poses significant challenges for decision-making. The most commonly-used "decision aid" processes, multi-criterion decision analysis (MCDA), multi-objective decision making (MODM), life cycle assessment (LCA) and cost-benefit analysis (CBA), utilise only limited numbers of qualities: refer to Section 2.[2] Elsewhere a participatory case study in bioenergy within the UK is described in which the diversity of qualities made decision-making using multi-criterion decision analysis (MCDA) impracticable [2]. MCDA utilises options, alternatives, attributes and criteria.

Novel decision processes are therefore needed to: (1) generate quantities of qualities; (2) program quantities-and-qualities from diverse choices; and (3) inform participants. Any of these may be a "weak link" in decisions. For example: (1) methods to aid decisions between quantitative options may be unsatisfactory; (2) narrow programming of quantitative-and-qualitative options may result in design that is not fit-for-purpose; or (3) the communication between "experts" and other participants may be poor.

In this paper, therefore, a novel iterative participatory decision-making process is proposed in which all these "weak links" are reinforced (Fig. 1). Participants may deliberate, and read and write narratives that can be analysed into qualities (step (3)). The use of narratives has been found to be a most effective method for the communication of science in public policy-making [3]. Computer support is able to program narrative qualities into quantities (step (1)) and back into qualitative narrative by, for example, constrained optimisation (step (2)).

The three steps just described are detailed in different sections of this paper. Step (1), described in Section 3, Framework development, requires that quantities are assigned to narrative qualities. The quantities and qualities may be expressed in "frameworks" for sustainable development, which may be developed from MCDA, MODM, LCA and CBA. Examples of "frameworks" are presented up to 64 qualities, with methods to define larger frameworks to be used in more complex decisions. In Section 4, Programming and Optimisation, step (2) of Fig. 1 is described. Programs are used to generate options qualities from quantities by optimisation. A program is presented to minimise risks subject to entropy constraints which are derived from definitions for thermodynamic and information entropy. Solutions are derived and it is shown that they are consistent with recent arguments presented in the literature regarding the relative sustainability of masses and values of stocks. In Section 5, Development of the program, the potential of the program is discussed including its participatory needs as illustrated in step (3) of Fig. 1. Conclusions are drawn in Section 6.

The frameworks have largely been developed within TSEC-Biosys, a NERC-funded project incorporating the use of sustainability assessment for the bioenergy sector of the UK, for the timescale from now until 2050 [4]. One of the original aims of this project was to develop a multi-criterion decision analysis and systems methodology for bioenergy to inform policy. Other publications in this project series describe focus groups and workshops by which this methodology was developed (e.g., [2,5]). These are listed at the end of this paper.

## 2. Review of processes of "decision aid"

Decision processes apply assessment and analysis iteratively. "Assessment" is "evaluation, estimation; an estimate of worth, extent, etc.". "Analysis" is "the resolution or breaking up of something complex into its various simple elements; the exact determination of the elements or components of something complex".

Hence assessment is concerned with what is valuable and achievable in a problem. This, equivalently, is represented in the norms, habits and personal characteristics of decision-makers. Analysis is concerned with what is acceptable and feasible in the problem. This, equivalently, is represented in the problem formulation. Tversky and Kahneman [6] demonstrated that decision "frames", meaning all aspects that affect decisions, are determined partly by the formulation of the problem and partly by the norms, habits and personal characteristics of decision-makers.

Assessments are varied and disparate among decision-makers. Their norms, habits and personal characteristics may include, for example, preferences for how to assess the problem and for particular outcomes. Assessment is a discursive and deliberative process,

[1] "Participants" are considered distinct from their bodies, which consist of qualities of "mass-equivalents". The distinction recognises participants' free will, and the determinism of mass qualities.

[2] In LCA, "mass-equivalent" is used as a unit. In other "decision aid" processes such as MCDA words such as "score" are used. "Mass-equivalent" is used here to enable an approach to decision-making that is interchangeable between quantities of "mass-equivalent" and qualities of "value": see section 4.

**Table 1**
Multi-criterion decision analysis framework.

| | |
|---|---|
| Option | Alternative |
| Criterion | Attribute |

best done through direct interaction. An important assumption is that those participating are willing to engage in the process to facilitate analysis, in other words, that the participants are willing to participate and are interested in rational outcomes. Strategic problems tend to require more discussion and deliberation than operational ones, since in the latter there is a clearer basis for consensus.

Analyses are diverse and balanced among the alternatives. The alternatives may include, for example, objectives or options. A preferred alternative is selected. The robustness of a selection is a measure of system evolution that results from a small change in the selection. Iterations occur as more information becomes available.

During analysis it is necessary to obtain information on the performance of all the alternatives. This can be done by the use of "decision aid" methods. Options can be rated relative to each other based on experience, or more extensive data gathering and quantitative modelling can be undertaken to obtain performance information. Important aspects for providing performance information include the quality of performance indicators used, or how good the indicator descriptions are. The type of indicators used is largely determined by the type of decision sought. The challenge is to be able to evaluate the alternatives based on a large number of attributes that may be expressed in incommensurate units. This process requires the exploration of the meaning of the alternatives in social deliberation with others [7].

We now review the decision aid processes MCDA, MODM, LCA and CBA. All of the reviews have the same structure, albeit with different qualities.

### 2.1. Multi-criterion decision analysis (MCDA)

MCDA is an *options* process about limited numbers of the qualities *attributes, alternatives* and *criteria*. In the usual course of an MCDA, the options are subject to "decision analysis" of attributes, alternatives and criteria; hence the name of the process (Table 1).

The purpose of an MCDA method is to construct a view or perception of preferences consistent with a certain set of assumptions, so as to give coherent guidance [8]. A variety of methods have been developed. A general classification of Belton and Stewart [8] as described in Mendoza and Martins [9] is shown in Table 2. More details of methods may be found in Keeney [10,11] and Belton and Stewart [8].

MCDA has been used in the selection of strategic energy supply options [12] and of contractors to design information systems [13].

### 2.2. Multi-objective decision making (MODM)

MODM is an *objectives* process about limited numbers of the qualities *decisions*, *constraints* and *weights* (Table 3).

The purpose of an MODM method is to construct a view or perception of cases consistent with a certain set of assumptions, so as to give coherent guidance. A variety of methods have been developed. A general classification is shown in Table 4. More details of methods may be found in Greening and Bernow [14], Cohon [15] and Keeney and Raiffa [10].

Because MODM is an informational optimisation process, it can be used to further producer interests. It has, for example, been used extensively by energy producers in risk management [12,14].

**Table 2**
Multi-criterion decision analysis methods: a general classification.

| | |
|---|---|
| Goal, aspiration or reference level | Desirable or satisfactory levels of achievement are established for each *criterion*. The process then seeks to discover *options* which are closest to achieving these desirable goals or aspirations |
| Valuation | Numerical scores are constructed in order to represent the degree to which one *option* may be preferred compared to another. Such scores are developed initially for each *criterion*, and are then synthesised in order to effect aggregation into higher level preference models. Though in practice valuation is not applied in such a rigid framework, this relatively strong set of axioms (a) imposes some form of discipline in the building up of preference models, (b) assists greater understanding of the values used, and the justification of the final decision when required, and (c) encourages explicit statements of acceptable trade-offs between *criteria* |
| Outranking | *Alternatives* are compared pairwise, initially in terms of each *criterion* in order to identify the extent to which a preference for one over the other can be asserted. In aggregating such preference information across all relevant *criteria*, the model seeks to establish the strength of evidence favouring selection of one *alternative* over another |

**Table 3**
Multi-objective decision making framework.

| | |
|---|---|
| Objective | Constraint |
| Weight | Decision |

**Table 4**
Multi-objective decision-making methods: a general classification.

| | |
|---|---|
| Goal, aspiration or reference level | Desirable or satisfactory levels of achievement are established for each *weight*. The process then seeks to discover *objectives* which are closest to achieving these desirable goals or aspirations |
| Valuation | Numerical scores are constructed in order to represent the degree to which one *objective* may make a case compared to another. Such scores are developed initially for each *weight*, and are then synthesised in order to effect aggregation into higher level case models. Though in practice valuation is not applied in such a rigid framework, this relatively strong set of axioms (a) imposes some form of discipline in the building up of case models, (b) assists greater understanding of the values used, and the justification of the final optimum when required, and (c) encourages explicit statements of acceptable trade-offs between *weights* (in Keeney and Raiffa [10]) |
| Outranking | Alternative *constraints* are compared pairwise, initially in terms of each *weight* in order to identify the extent to which a case for one over the other can be asserted. In aggregating such case information across all relevant *weights*, the model seeks to establish the strength of evidence favouring selection of one *constraint* over another (in Cohon [15]) |

### 2.3. Life cycle assessment (LCA)

LCA is an *assessment* process about limited numbers of the qualities *functions, cycles* and *lives* (Table 5).

The purpose of an LCA method is to construct a view or perception of needs consistent with a certain set of assumptions, so as to give coherent guidance. A variety of methods have been developed. A general classification is shown in Table 6. More details of

**Table 5**
Life cycle assessment framework.

| | |
|---|---|
| Assessment | Cycle |
| Life | Function |

**Table 6**
Life cycle assessment methods: a general classification.

| | |
|---|---|
| Goal, aspiration or reference level | Desirable or satisfactory levels of achievement are established for each *life*. The process then seeks to discover *assessments* which are closest to achieving these desirable goals or aspirations |
| Valuation | Numerical scores are constructed in order to represent the degree to which one *assessment* may be needed compared to another. Such scores are developed initially for each *life*, and are then synthesised in order to effect aggregation into higher level needs models. Though in practice valuation is not applied in such a rigid framework, this relatively strong set of axioms (a) imposes some form of discipline in the building up of needs models, (b) assists greater understanding of the values used, and the justification of the final assessment when required, and (c) encourages explicit statements of acceptable trade-offs between *lives* |
| Outranking | Alternative *cycles* are compared pairwise, initially in terms of each *life* in order to identify the extent to which a need for one over the other can be asserted. In aggregating such needs information across all relevant *lives*, the model seeks to establish the strength of evidence favouring selection of one alternative *cycle* over another |

**Table 8**
Cost-benefit analysis methods: a general classification.

| | |
|---|---|
| Goal, aspiration or reference level | Desirable or satisfactory levels of achievement are established for each *project*. The process then seeks to discover *analyses* which are closest to achieving these desirable goals or aspirations |
| Valuation | Numerical scores are constructed in order to represent the degree to which one *analysis* may be timed compared to another. Such scores are developed initially for each *project*, and are then synthesised in order to effect aggregation into higher level temporal models. Though in practice valuation is not applied in such a rigid framework, this relatively strong set of axioms (a) imposes some form of discipline in the building up of temporal models, (b) assists greater understanding of the values used, and the justification of the final analysis when required, and (c) encourages explicit statements of acceptable trade-offs between *projects* |
| Outranking | Alternative *costs* are compared pairwise, initially in terms of each *project* in order to identify the extent to which a time for one over the other can be asserted. In aggregating such temporal information across all relevant *projects*, the model seeks to establish the strength of evidence favouring selection of one alternative *cost* over another |

methods may be found in Baumann and Tillman [16] and Guinée [17].

Because LCA is an environmental assessment process, it can be used to further public interests. It has, for example, been adopted for developing information for use in the ecolabelling of products in the EU [18]; it has also found application in the development of Integrated Product Policy [19].

### 2.4. Cost-benefit analysis (CBA)

CBA is an *analysis* process about limited numbers of the qualities *benefits, costs* and *projects* (Table 7).The purpose of a CBA method is to construct a view or perception of time consistent with a certain set of assumptions, so as to give coherent guidance. A variety of methods have been developed. A general classification is shown in Table 8. More details of methods may be found in Boardman et al. [20].

Because CBA is an economic analysis process, it can be used to further private interests. It has, for example, been popular for many years as a means of supporting investment decision-making.

## 3. Framework development

### 3.1. Definitions

A "quality" is *a kind of* [specified thing]. A "quantity" is *a property of a* [specified thing] *that is estimable by some sort of measure* (source: Shorter Oxford English Dictionary). "Nought" is the quality with quantity 0.

"Mass-equivalents" are assumed, measured in kg, J or equivalent.

### 3.2. Methodology

Propositional logic demonstrates that any narrative phrase can be logically written as quantities and qualities connected by "and", "of" or "not", and can be established from the truth or falsity of the original quantities and qualities [21]. For any such phrase, a quantity can be calculated by replacing each quality with its quantity, and each of "and", "of" and "not" with +, $\times$ and $-$, respectively.

As an example, note that an option "of" any quality is always the same quality. Therefore, let us define the quantity of "option" as $a$ and the quantity of the quality as $b$. Because "of" is replaced by x, we have $a \times b = b$. It follows that $a = 1$, so that the quantity of "option" is 1. The quality and quantity of "option" may be written thus: option (1).

Next, referring to the definitions beyond Table 10 if desired, observe that option (1) "and" option (1) is alternative $(1 + 1 = 2)$; alternative (2) "and" option (1) is criterion $(2 + 1 = 3)$; criterion (3) "and" option (1) is assessment $(3 + 1 = 4)$; alternative (2) "of" alternative (2) is assessment $(2 \times 2 = 4)$; and assessment (4) "and" option (1) is attribute $(4 + 1 = 5)$. Quantities of qualities preceded by "not" are negative; for example, not a criterion "and" criterion is nought $(-3 + 3 = 0)$.

Table 9 shows the $2 \times 2$ framework for the quantities 1, 2, 3 and 5; it will be observed that it is identical to the framework for multi-criterion decision analysis (Table 1). As in other frameworks presented in this section, some quantities (in this case 4) are omitted; however for any quantity, it is always possible to find a large enough framework containing it, because the numbering system used is alternately diagonal from the top-left to ensure consistency between frameworks of different sizes (quantity 4 appears in the framework of Table 10).

From Table 9, larger frameworks can be extended. Table 10 and its associated definitions form a proposal for the $8 \times 8$ framework. Within Table 10: alternative "of" criterion is analysis $(2 \times 3 = 6)$; and, for example, criterion "of" governance is data $(3 \times 28 = 84)$. The methodologies MCDA, CBA, LCA and MODM are integrated and appear as the $4 \times 4$ framework in the top-left of Table 10. The "lobes" of sustainable development: option, economic, social and environmental form the corners of the $6 \times 6$ framework [22]. Using larger tables there could be represented, for example: cathedral "and" town is city; sunlight "and" carbon dioxide "and" water "and" green plant is sugar "and" oxygen, and so on.

**Table 7**
Cost-benefit analysis framework.

| | |
|---|---|
| Analysis | Cost |
| Project | Benefit |

**Table 9**
$2 \times 2$ framework (as Table 1).

| | |
|---|---|
| 1. Option | 2. Alternative |
| 3. Criterion | 5. Attribute |

**Table 10**
Proposal for 8 × 8 framework.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1. Option | 2. Alternative | 6. Analysis | 7. Cost | 15. Need | 16. Environmental | 28. Governance | 29. Development |
| 3. Criterion | 5. Attribute | 8. Project | 14. Benefit | 17. Management | 27. Preference | 30. Sustainable | 44. Participatory |
| 4. Assessment | 9. Cycle | 13. Objective | 18. Constraint | 26. Material | 31. Impact | 43. Work | 48. Turnover |
| 10. Life | 12. Function | 19. Weight | 25. Decision | 32. Fate | 42. Inventory | 49. Exposure | 63. Emission |
| 11. Case | 20. Scenario | 24. Choice | 33. Production | 41. Demand | 50. Equity | 62. Consumption | 71. Policy |
| 21. Economic | 23. Temporal | 34. Service | 40. Uncertainty | 51. Supply | 61. Social | 72. Private | 86. Stock |
| 22. Spatial | 35. Price | 39. Design | 52. Specification | 60. Knowledge | 73. Public | 85. Flow | 98. Boundary |
| 36. Purchase | 38. Value | 53. Narrative | 59. Description | 74. Potential | 84. Data | 99. System | 113. Unit |

1. *Option*: a thing that is or may be chosen.
2. *Alternative*: stating or offering either of two things; expressing alternation; disjunctive.
3. *Criterion*: a principle, standard or test by which a thing is judged, assessed or identified.
4. *Assessment*: evaluation, estimation; an estimate of worth, extent, etc.
5. *Attribute*: a quality or character ascribed to a person or thing.
6. *Analysis*: the resolution or breaking up of something complex into its various simple elements; the exact determination of the elements or components of something complex.
7. *Cost*: what must be given in order to acquire, produce or effect something.
8. *Project*: a planned or proposed undertaking; a scheme.
9. *Cycle*: a recurrent period of definite duration.
10. *Life*: the condition, quality or fact of being a living organism; the condition that characterizes animals and plants (when alive) and distinguishes them from inanimate matter, being marked by a capacity for growth and development and by continued functional activity; the activities and phenomena by which this is manifested.
11. *Case*: an instance of a thing's occurrence.
12. *Function*: the activity proper or natural to a person or thing; the purpose or intended role of a person or thing.
13. *Objective*: of or pertaining to an object or end as a cause of action.
14. *Benefit*: (an) advantage, (a) good.
15. *Need*: necessity for a course of action arising from facts or circumstances.
16. *Environmental*: of or pertaining to the (physical) environment.
17. *Management*: the application of skill or care in the manipulation, use, treatment or control of things or persons, or in the conduct of an enterprise, operation, etc.
18. *Constraint*: something that restricts freedom of action.
19. *Weight*: a relative value assigned to an observation, factor, etc.
20. *Scenario*: a description of an imagined situation or a postulated sequence of events.
21. *Economic*: relating to the management of private, domestic, etc., finances.
22. *Spatial*: of or relating to space; subject to or governed by the conditions of space, frequently as opposed to those of time.
23. *Temporal*: lasting or existing only for a time; passing, temporary.
24. *Choice*: choosing, deciding between possibilities; a necessity to choose.
25. *Decision*: the action of coming to a determination or resolution with regard to any point or course of action; a resolution or conclusion arrived at.
26. *Material*: of or pertaining to matter or substance; formed or consisting of matter.
27. *Preference*: the quality of being preferable; precedence, superiority.
28. *Governance*: the action, manner or fact of governing; government.
29. *Development*: the process of coming into existence or operation.
30. *Sustainable*: able to be maintained at a certain rate or level.
31. *Impact*: the (strong) effect of one thing, person, action, etc., on another; an influence; an impression.
32. *Fate*: that which is destined to happen; a thing's appointed lot.
33. *Production*: the action or an act of producing, making, or causing something; the fact or condition of being produced.
34. *Service*: work undertaken according to the instructions of an individual or organization.
35. *Price*: the sum in money or goods for which a thing is or may be bought or sold.
36. *Purchase*: that which is obtained or acquired; gains, winnings.
38. *Value*: that amount of a commodity, medium of exchange, etc., considered to be an equivalent for something else; a fair or satisfactory equivalent or return.
39. *Design*: a purpose, an intention, an aim.
40. *Uncertainty*: the state of being uncertain; doubtfulness; hesitation; irresolution.
41. *Demand*: a call for a commodity or service.
42. *Inventory*: a detailed list of items such as goods in stock, a person's property, the contents of a storage box, room, building, etc., occasionally with a statement giving the nature and value of each item.
43. *Work*: a thing done; an act, a deed, a proceeding involving toil or strenuous effort.
44. *Participatory*: characterized by decision-making; especially in an organization, community or society; allowing members of the general public to take part.
48. *Turnover*: the amount of goods produced and disposed of by a manufacturer.
49. *Exposure*: the action of exposing; the fact or state of being exposed.
50. *Equity*: the recourse to general principles of justice to correct or supplement common or statute law; the part of a legal system based on this.
51. *Supply*: something supplied, a stock or store of something provided or obtainable.
52. *Specification*: an explicit or detailed enumeration (of).
53. *Narrative*: an account of a series of events, facts, etc., given in order and with the establishing of connections between them; a narration, a story.
59. *Description*: an account of a person, thing, scene or event; a verbal portrait.
60. *Knowledge*: the fact of knowing a thing, state, person, etc.; acquaintance; familiarity gained by experience.
61. *Social*: of or pertaining to the mutual relationships of human beings or of classes of human beings; connected with the functions and structures necessary to membership of a group or society.
62. *Consumption*: the action or fact of consuming.
63. *Emission*: the action of sending out something or someone.
71. *Policy*: a course of action or principle adopted or proposed by a government, party, individual, etc.; any course of action adopted as advantageous or expedient.
72. *Private*: provided or owned by an individual rather than the state or a public body.
73. *Public*: of or pertaining to the people as a whole.

**Table 11**
Definitions of entropy.

| |
|---|
| "Mass (thermodynamic) entropy" is defined for mass-equivalents with probabilities $p_i$ (for which $\Sigma\ p_i = 1$) within a bounded system by: |
| $H^T = -k\sum p_i \log p_i$, |
| Sethna [34], where $k > 0$ is the Boltzmann constant in $\mathrm{JK}^{-1}$, and K is the (absolute) temperature (heat index) scale. Any increase of mass-equivalents in the system will increase $H^T$. |
| "Information (economic) entropy" is defined for information-equivalents with values $v_i$ (for which $\Sigma\ v_i = 1$) within a bounded system by: |
| $H^I = -c\sum v_i \log v_i$, |
| Shannon [35], where $c > 0$ is a constant with unit £$\mathrm{I}^{-1}$, and I is an (absolute) price index scale. Any increase of information-equivalents in the system will increase $H^I$. |

74. *Potential*: possible as opposed to actual; capable of coming into being or action; latent.
84. *Data*: things given or granted; things known or assumed as facts, and made the basis of reasoning or calculation.
85. *Flow*: any continuous movement resembling the flow of a river and connoting a copious supply; an outpouring, a stream.
86. *Stock*: a store of goods available and on hand for sale, distribution, etc.
98. *Boundary*: a thing which serves to mark the limits of something; the limit itself, a dividing line.
99. *System*: a group or set of related or associated material or abstract things forming a unity or complex whole.
113. *Unit*: an individual thing, person or group regarded as single and complete, especially for the purposes of calculation; each of the (smallest) separate individuals or groups into which a complex whole may be analysed.

(Source: Shorter Oxford English Dictionary)

## 4. Programming and optimisation

A method of frameworks has been described for attaching quantities to statement qualities. Its purpose is to enable decision-making. Decision-making can be taken against both mass-energy and value. Values are supplied by the framework's quantities of the decision-maker's qualities (for example, the value of "objective" is 13; the value of "constraint" is 18) and "normalised" so that they are positive and sum to 1. Mass-equivalents are measured and "normalised" likewise. In this section we are concerned with optimising sums and products of these "mass-equivalents" and "values", which we may call (quantitative-and-qualitative) "risks".

The choices for such optimisation programs are constrained by laws independent of any specific qualities or quantities. The laws concern mass-equivalents and values bounded within a system. They are therefore, respectively, laws of mass-energy and information, and in particular, because quantities are concerned, the laws of "entropy". In Table 11 we present the definitions of "mass (thermodynamic) entropy" $H^T$ and "information (economic) entropy" $H^I$.

Within this approach, events of transport of mass and transmission of information may be interchanged. Thus expressions for "mass (thermodynamic) entropy" and "information (economic) entropy" can be equated to within the constants $k$ and $c$:

$$\frac{H^T}{k} = \frac{H^I}{c} \tag{1}$$

$$\sum p_i \log p_i = \sum v_i \log v_i \tag{2}$$

This constraint always applies; within it there is a choice of programs to optimise quantitative-and-qualitative expressions. Here we choose to minimise the program risk expression $\Sigma p_j v_j$.

### 4.1. Lagrangian minimisation of program risk value subject to constraint

From Eq. (2) it follows from the independence of the $p_i$ and $v_i$ that:

$$p_1{}^{p_1} p_2{}^{p_2} \ldots p_n{}^{p_n} = v_1{}^{v_1} v_2{}^{v_2} \ldots v_n{}^{v_n} \tag{3}$$

By taking derivatives of Eq. (2) with respect to time $t$, we also have:

$$\sum_i \frac{\partial p_i}{\partial t}(\log p_i + 1) = \sum_i \frac{\partial v_i}{\partial t}(\log v_i + 1) \tag{4}$$

Eq. (3) restates a result of Section 3: the meaning of any quantity-and-quality expressed in factors $p_1{}^{p_1} p_2{}^{p_2} \ldots p_n{}^{p_n}$ does not depend on the factors used. Eq. (4), equivalently, links stocks $p_i$ and flows $\partial p_i/\partial t$, with values $v_i$ and prices $\partial v_i/\partial t$.

A numerical method of solution for the optimisation problem is indicated (Table 12). The constraints also include known quantities of $(p_i, v_i)$; for example, the quantities may be made to be greater than

**Table 12**
Solution to Lagrangian minimisation of program risk subject to entropy constraint.

Minimise $\sum_j p_j v_j$ such that $p_1{}^{p_1} p_2{}^{p_2} \ldots p_n{}^{p_n} = v_1{}^{v_1} v_2{}^{v_2} \ldots v_n{}^{v_n}$;

$0 \le p_i \le 1$; $0 \le v_i \le 1$; $\sum_j p_j = \sum_j v_j = 1$; some $p_i's > k_i's$ or $= k_i's$; some $v_i's > c_i's$ or $= c_i's$.

Define Lagrangian

$$L = \sum_j p_j v_j + \lambda(v_1{}^{v_1} v_2{}^{v_2} \ldots v_n{}^{v_n} - p_1{}^{p_1} p_2{}^{p_2} \ldots p_n{}^{p_n}) + \mu(1 - \sum_j p_j) + \nu(1 - \sum_j v_j) + \text{terms relating to } p_i \text{ and } v_i \text{ constraints}$$

For optima:

$\frac{\partial L}{\partial p_i} = v_i - \lambda(\log\ p_i + 1) p_1{}^{p_1} p_2{}^{p_2} \ldots p_n{}^{p_n} - \mu = 0$; (1)

$\frac{\partial L}{\partial v_i} = p_i - \lambda(\log\ v_i + 1) v_1{}^{v_1} v_2{}^{v_2} \ldots v_n{}^{v_n} - \nu = 0$; (2)

$\frac{\partial L}{\partial \lambda} = 0 \Rightarrow p_1{}^{p_1} p_2{}^{p_2} \ldots p_n{}^{p_n} - v_1{}^{v_1} v_2{}^{v_2} \ldots v_n{}^{v_n} = 0$; (3)

$\frac{\partial L}{\partial \mu} = 0 \Rightarrow \sum_i p_i - 1 = 0$; and $\frac{\partial L}{\partial \nu} = 0 \Rightarrow \sum_i v_i - 1 = 0$. (4) and (5); and equations corresponding to $p_i$ and $v_i$ constraints.

Numerical methods are required. An approximate solution is used to yield a gradient to the solution from these equations, from which a better approximation is derived by the Newton Raphson or other ascent methods [33].

or equal to known quantities ($p_i >=$ a constant; $v_j >=$ a constant for some $i$'s and $j$'s); these constraints limit the solution set.

For each set ($p_i$,$v_i$) the solution set has a minimum. As $p_i \to 0$, $v_i$ becomes positive for every set $p_i$; and as $v_i \to 0$, $p_i$ becomes positive for every set $v_i$. In other words, "uncommon" qualities tend to have high costs and prices; "common" qualities tend to have low costs and prices; "expensive" prices tend to have high quantities and qualities; and "cheap" prices tend to have low quantities and qualities. If the value of a price > the value of a cost, the quality is worth selling; otherwise, the quality is worth buying; if the value of a quantity > the value of a quality, the quality is worth processing; otherwise, the quality is not worth processing.

The solution may be interpreted as the material fractions and values that provide optimal program risk value from a social material or waste stream. Within such a waste stream, small fractions by weight have the most significant value, while large fractions do not. The analysis provides support for arguments recently put forward in a paper by Clift et al. [23] regarding the sustainability of international supply chains, in which certain particularly uncommon materials, such as objets d'art and designer clothing are accorded high value.

## 5. Development of the program

Here is outlined in more depth some of the steps that may be necessary to bring about the program described, and some of the developments that may result.

### 5.1. Development of qualities

This program is a process of gradual change and is therefore evolutionary. As it proceeds, "options" of qualities may start to be expressed more usually as qualities of constituents of "options". Qualities consist of countable numbers of connected words such as are shown in Table 10. All words are expressed in finite dictionaries in terms of other words and connectives. Therefore all qualities will eventually appear in extensions of Table 10.

As gradual change starts to be replaced by ever more variable change, a priority for decision-making will become the provision of diverse, comprehensible information from participation. This enables more definite plans to be made of intended proceedings for constituents of "options". Greater choice should result, increasingly for more specific and potentially smaller participatory groups. This process has already begun through the wide spread of information technology.

Information can be used to communicate most effectively to participants when it is comprehensible. Recent case studies illustrate the effectiveness of "narratives" in participatory communication [5,24,25]. Whether used in group or individual participation, "narratives" are likely to be far more effective at enabling communication with non-specialists than other forms of presentation, as they are expressed in participant language. The use of "narratives" in participation corresponds to step (3) of Fig. 1.

### 5.2. Development of quantities

Computer support will be able to store the quantities of qualities in a database and recover them. For example, from the database a look-up for 6 will yield the quality "analysis". "Prime" qualities may be defined as those with prime quantities. Any quality may be uniquely written in terms of its "prime" qualities and the connective "of" by factorising its quantity into primes. Qualities may not be so uniquely written in terms of other factors, and such choices of expressions will be programmed.

By extension to the approach, it will be possible to carry out: (1) analysis, which will work out a quantity for any quantitative-and-qualitative document; (2) assessment, of programmed quantities-and-qualities for any quantitative-and-qualitative document. This approach will yield an enormous amount of choice from different programming methods.

Performing both (1) and (2) is relatively straightforward given any database of numbered qualities, using the rules given for the connectives. There are over one million words in the English language today, if American forms are included; a graduate's working vocabulary is 20,000 words. Sentence phrases usually have only a handful of qualities, so that documents written in English can typically be quantified within computational limits. Common spreadsheets permit integers up to $10^{12}$ without modification; it is possible to go much higher. The prime factorisation of such numbers is not problematic; primes to $10^6$ are commonly available and much higher ones can be generated easily.

### 5.3. Challenges to implementation

If embraced, growth of computational support to the program is likely to widen choice significantly through the diversity of qualities made available. The starting point for defining qualities should be good dictionaries and the integrated programming of basic arithmetical operations. It will be very important that evolving programs and frameworks receive wide social acceptance. In order to achieve this, evolving case study work, particularly in "decision aid" will be critical. The development of methods for participation and governance will probably matter more than anything. A description of the state-of-the-art in such methods is beyond the scope of this paper; the reader is referred to recent case study descriptions such as Renn et al. [26] and Petts [27]. Stirling [28] has recently highlighted means by which participatory processes can "open up" appraisal processes, by adopting a focus on revealing to wider policy discourses the detailed implications of different sources of information and the role of different disciplines, divergent social values and conflicting interests in conditioning disparate interpretations of the available evidence. The discipline of "programming" as described in this paper will provide a comprehensive mechanism for this focus. Key to evolving case studies must be a concentration on representative public engagement, nevertheless many of these and other examples highlight its costs [29]. The costs of public engagement, substantial or not, are likely to be vital in determining any further evolution of the program towards automation. The approach provides the capability for unlimited progress in this direction using quantities of any magnitude, but informed public debate and governance will be of the essence. Hence the necessity of a gradual program.

## 6. Conclusions

The evolution of decision-making is likely to continue to lead to the emergence of ever more diverse complex systems which challenge the simplistic approaches of current decision aid methods. These complex systems have emergent properties that depend on the interactions between their constituent parts, and that "lead to a recursive approach to decision-making, with MCDA [and other decision aid processes] being an example" [30]. In this paper, a recursive program has been set out for sustainable development and participatory governance, and it has been indicated how it may be expressed in qualities and quantities. The structures of sustainable development frameworks up to 64 qualities have been described, including the frameworks for the key methods of decision aid multi-criterion decision analysis (MCDA), multi-objective decision making (MODM), life cycle assessment (LCA) and cost-benefit analysis (CBA), which have been reviewed. It has been

shown that the structure of all these frameworks is the same and that it is based on MCDA.

The 64-quality framework of Table 10 provides a structure within which the integrations of the existing methodologies can now be accomplished in case study work. More work on the structure can provide more qualities: programmers identify the qualities to assign to the lowest numbers, with others being multiples. The order in which numbers are assigned is decided by the programmer(s) who may or may not be decision-makers or even participants; since all programs are always of finite length their choices have to be apposite. Given the propensity of humans to unethical behaviour, it is the responsibility of decision-makers to conduct reviews of program qualities prior to use.

At rock bottom, many might argue that the most pressing issue is the integration of life cycle assessment (LCA) with footprinting methodologies. This integration, carried out in case studies with carbon dioxide equivalents selected as the functional unit, enables bounded systems to be compared and decided upon with respect to objectives, weights and constraints related to the risks of climate change. Such a facility could prove useful in negotiations between authorities in different geographical regions. The framework permits the negotiations to be conducted in “narrative”, improving the quality of participant comprehension [5]. It also enables uncertainty, quality 40, to be probabilistically specified. The integration of the consideration of uncertainty into decision-making was identified as a pressing need for policy a long time ago [31]. Table 10 exhibits qualities such as “knowledge”, “policy” and “equity”. The decision-making of such qualities, of course, influences system boundaries, stock units, and flows, turnover and exposure. The system can be described by attributional LCAs ($5 \times 13$), while scenarios ($4 \times 5$) can be described with the aid of consequential LCAs ($9 \times 5$). Use can be included in the framework as case of an objective ($11 \times 13$). The full integration of land use with consequential LCA is still relatively unexplored (e.g., [32]) yet it is of high policy significance.

This 64-quality framework should support better decision-making on all of these issues. However it already seems likely that, in time, there will be even greater demand for use of these methodological approaches: the diversity of mass- and information-equivalent qualities is continuing to rise in many applications, including in healthcare, transport, manufacturing industry and others. The approaches of Section 4, applied with appropriately extended frameworks, have the potential to offer a means to the integration of all quantities and qualities within the evolutionary program described.

## Related papers planned for the TSEC-Biosys “Describing the elephant” series

1. Sinclair P, Cohen B, Hansen Y, Basson L, Clift R. Stakeholder engagement within the sustainability assessment of bioenergy: case studies in heat, power and perennial and annual crops from the UK. Four bioenergy focus groups are described, one in woodfuel for heat and one in woodfuel for power (held in Yorkshire, England); and one in perennial crops and one in annual crops (held in Dorset, England), at which decision-making criteria were elicited from local stakeholders. The criteria were very diverse, making the application of Multi-Criterion Decision Analysis (MCDA) impracticable.
2. Sinclair P, Clift R. Planning a bioenergy research project: a participatory workshop in narrative structuring. A bioenergy project research workshop held with experts is described. Its aim was to reduce the diversity of criteria collected in paper 1 to a manageable set which could form a basis for informing project development.
3. Sinclair P, Lovell J, Clift R. Participation in the sustainability assessment of bioenergy: some case study methods and their evaluation. Some case study methods in the sustainability assessment of bioenergy, and their evaluation, are described.
4. Sinclair P, Ogunkunle D, Clift R. Participatory policy-making for sustainable development: a case study workshop. A participatory process case study design and implementation for a two-day UK bioenergy policy-making workshop is described. The implementation was evaluated by the participants and shown to demonstrate the essential process design features for sustainable development and participatory governance.
5. Hector D, Petrie J, Clift R, Cohen B, Sinclair P, Ogunkunle D. Developing a qualitative dynamic model of the UK bioenergy system for multi-criteria analysis. The development of a qualitative dynamic model of the UK bioenergy system for multi-criteria analysis is described, from which UK bioenergy narratives were subsequently written.
6. Ogunkunle D, Sinclair P, Clift R. Evaluating UK bioenergy narratives for policy development: a novel application of Q methodology and content analysis. The UK bioenergy narratives of paper 5 are described and evaluated for policy development, and novel applications of the ‘Q’ methodology and content analysis are presented.
7. Jablonski S, Strachan N, Brand C, Bauen A. The role of bioenergy in the UK’s energy future. Formulation and Modelling of Long-term UK bioenergy scenarios. Long-term UK bioenergy scenarios are formulated and modelled.
8. Ogunkunle D, Jablonski S, Sinclair P, Clift R. Implications of Long-term UK bioenergy scenarios based on stakeholder concerns. The implications of the long-term UK bioenergy scenarios of paper 7 are described and analysed.

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